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DEVELOPMENT OF COMPUTER-INTEGRATED SYSTEMS FOR THE AUTOMATION OF TECHNOLOGICAL PROCESS OF ASSOCIATED GAS PROCESSING

A. Stopakevych
PhD, Associate Professor*
E-mail: stopakevich@gmail.com
O. Stopakevych
PhD, Associate Professor
Department of automation of power processes
Odessa National Polytechnic University
Shevchenko ave., 1, Odessa, Ukraine, 65044
A. Tigariev
PhD, Associate Professor*
E-mail: amtigar@ukr.net
*Department of computer-integrated technological processes and industries
Odessa national academy of telecommunications named after O. S. Popov
Kuznechna str., 1, Odessa, Ukraine, 65029

Проаналізована переробка супутнього нафтового газу. Запропонована процедура побудови комп'ютерно-інтегрованої системи автоматизації технологічного процесу переробки газу. Особливістю процедури є комплексне розв'язання задачі ефективного розрахунку технологічного процесу і керування їм сучасною системою керування. Процедура використана для розробки технологічного процесу переробки газу нафтового родовища середньої потужності. Процес забезпечує якісну переробку газу при значних збуреннях

Ключові слова: ректифікація, метан, пропан-бутан, система автоматичного керування, комп'ютерно-інтегрована автоматизація

Проанализирована переработка попутного нефтяного газа. Предложена процедура построения компьютерно-интегрированной системы автоматизации технологического процесса переработки газа. Особенностью процедуры является комплексное решение задачи эффективного расчета технологического процесса и управления им современной системой управления. Процедура использована для разработки технологического процесса переработки газа нефтяного месторождения средней мощности. Процесс обеспечивает качественную переработку при значительных возмущениях

Ключевые слова: ректификация, метан, пропан-бутан, система автоматического управления, компьютерно-интегрированная автоматизация

1. Introduction

The use of associated petroleum gases (APG) is an important line of increasing efficiency of oil well operation. The problem is given a considerable attention both by governments and businesses of a number of leading oil-producing countries [1, 2].

Ukraine is potentially capable to satisfy all domestic demands for oil and gas [3]. For economic and political reasons, it has been more profitable in the past to import oil and gas, however, due to the recent change in the world political situation, the urgency of developing and improving efficiency of using own oil and gas fields has increased significantly. It is unacceptable that about 75 % of Ukrainian APG is not utilized but burnt in torches [4]. In this work, detailed data on composition of Ukrainian APG deposits are presented. In addition to the negative effects to environment, burning of gas is simply economically unjustified in most cases. There are no legislative regulations for APG utilization and processing methods in Ukraine.

The technical side of the APG processing problem is connected with the computer-integrated automation of the technological process (TP) of APG processing with its productivity tied to the current field productivity.

The main principles underlying the proposed procedure are as follows:

– automation of the technological process development;

– computerized integration of the process equipment and the automatic process control system;

– strict binding of the technological equipment parameters and the plant operating condition parameters to the specific features of a real oil field, to the requirements of the finished product market;

– taking into account interconnection between statics and dynamics of the technological process in synthesis of the automatic control system.

2. Literature review and problem statement

An overview of current trends in the oil and gas market is given in work [5]. Software for designing the TP of APG processing is currently available. An up-to-date review of the software is given in [6]. Variety of software, study of its operating features, advantages and disadvantages in solving specific problems constitute the problematics of efficiency of its use. Such efficiency can be achieved with the help of an integrated approach which was formulated in [7].

The approach allows overcoming the following contradictions arising in the process of TP development and the automatic control system (ACS) designing for the TP:

– between achievement of optimality of each unit operating conditions and optimality of the entire TP including recycles;

– between achievement of optimality of technological calculation and the optimality of TP control;

– between the convenience of using linear mathematical models and controllers in construction of TP ACS and the nonlinear behavior of real TP units.

The approach assumes the use of universal software of technological process simulation (USTPS). The use of USTPS for the TP design was discussed in [8–10]. In the above studies, the HYSYS USTPS was used [11].

The work [8] considered the problem of optimal design of the technological process for APG which was supplied to one of the gas processing plants (GPP) in Bangladesh. Disadvantage of this work is that the working capacity of the technological process was not considered when alterations in the composition of the incoming APG take place and the issue of potential controllability of the manufacturing scheme with the aid of the automatic control system was not investigated.

Manufacturing scheme of APG processing at the Pakistan GPP was considered in [9]. The scheme assumes separation of commercial methane, a pure mixture of propane-butane (LPG) and a liquid gas fraction (LNG). The influence of disturbances in flow, composition, and pressure of incoming APG was investigated. An approach was proposed to the choice of such temperature conditions which will make it possible to obtain satisfactory results of TP design in a case when deviations from parameters, composition and concentration of APG occur. Its disadvantage consists in the absence of a formulated optimization technique and the lack of attention to optimizing parameters of the distillation columns and other units to improve controlability of objects with the help of ACS. Thus, a situation is possible during the real TP functioning when a theoretical possibility of transition from one mode of operation to another will be practically impracticable under the influence of disturbances.

In [10], the manufacturing scheme of processing the gas coming from the Egyptian GPP was considered. Economic optimization of the equipment operation parameters of the existing manufacturing scheme for the specified composition of incoming gases was considered. The issues of alteration of gas composition and controllability were not considered in this work.

The Ukrainian oil fields feature their relatively low capacity and territorial dispersion [3]. Of all 400 known deposits, only 37 have been developed, among them 3 large, 27 medium and 7 small ones. APG of these deposits is characterized by high contents of methane and butanes, calorific value, low content of pentanes. Thus, the analysis shows that designing of gas processing plants (GPP) of small and medium capacity located geographically near the oil fields is optimal for medium oil fields with APG. Such plants are called local gas processing plants (LGPP).

3. The aim and objectives of the study

The study purpose was development of a computer-integrated system for the automation of LGPP.

To achieve this goal, the following tasks were accomplished:

– development of a procedure for construction of a computer-integrated system for automating technology of processing associated petroleum gas;

– development of an automated TP for processing APG from the fields of low and medium productivity based on the proposed procedure.

4. Materials and methods of studying ways of solving problems of development of computer-integrated automation of technological processes

The schematic diagram of the developed procedure for constructing a computer-integrated automation system for the TP of APG processing is shown in Fig. 1.

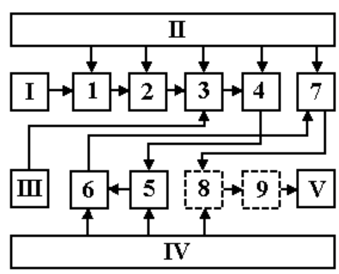


Fig. 1. Schematic diagram of the developed procedure for construction of a computer-integrated system for automation of the technological process: I - data on APG composition; II – HYSYS software; III – Chemsep and heat exchanger calculation software; IV – Matlab software; V – real technological process; 1 – development of a schematic diagram of the technological process; 2 – calculation of main parameters of the technological process; 3 – analysis of disturbances and optimization of operation parameters of the process equipment units; 4 – choosing the strategy for controlling parameters of the technological process; 5 – study of TP dynamics and construction of simplified linear mathematical models; 6 – synthesis of controllers for automatic control systems and simulating linearized automatic control system; 7 – simulating automatic control system at a nonlinear object; 8 – implementation of control in the real-time system; 9 – technical means of automation with network architecture

The procedure involves performance of a specified sequence of operations. If problems arise in performing any of the operations, it is necessary to turn back to the previous operations. The main advantage of the procedure is ability to identify and overcome contradictions that arise when solving the tasks of technological calculation and synthesis of automatic control systems. Attention to these contradictions arises due to the need of development of a technological process, which would be both effective in statics and operable at large disturbances in dynamics.

A brief description of the research methods used in development of recommendations for operations 1–7 of the procedure is given in Table 1. Implementation of blocks 8 and 9 (Fig. 1) of the procedure was fairly obvious and was not considered in this study.

Table 1

Research methods used in the procedure of computer-integrated process automation

Operation No.	Research methods
1	Analysis of composition of APG of Ukrainian deposits, generalization of the results obtained in literature analysis, use of USTPS
2	Decomposition of TP. Choice of temperature conditions using USTPS according to the boiling point of gas mixtures. Selecting the installation operation parameters using a simplified calculation
3	Analysis of the TP functioning when flow, composition, and temperature of APG change in a case of simulating in USTPS. Parametric optimization of parameters of TP devices taking into account limitations
4	Analysis of features of the sensors and actuators of the technological process under consideration, summary of the results obtained in analysis of the literature on automation of the TP and its individual units
5	Planning an active experiment in USTPS. Identification of channel models by simplified and accurate linear systems
6	Methods of synthesis of single-loop automatic control systems. Methods of synthesis of optimal multivariable automatic control systems. Methods of parametric optimization of parameters of ACS controllers. Methods for simulating linear automatic control systems
7	Methods of simulating nonlinear automatic control systems. Methods for analyzing quality of transient processes in automatic control systems

The efficiency criterion of the TP developed on the basis of the proposed procedure consists in the required quality of the transient processes in the TP automatic control system for APG processing at maximum disturbances.

The software used in implementation of the procedure included the following programs.

1. HYSYS USTPS [11]. The software enables simulation of statics and dynamics of oil and gas TPs. Most technological devices are modeled with a high coincidence of technological parameters with their values in a real technological process. This is achieved by taking an accurate account of thermodynamic and chemical transformations. It is convenient to develop macros in the built-in WrapBasic language. There is a software interface for interprogram communication.

2. Chemsep software for optimization calculation of statics of distillation columns (DC) [12]. The program is characterized by high calculation speed, it supports distillation columns of different types and ensures coincidence of calculation results with real DC operation.

3. The program for calculating heat exchangers [13]. It ensures optimization calculation of the design parameters of heat exchangers. Calculation of optimum parameters of the single-loop automatic control system on the basis of the PID family controllers can also be made.

4. Matlab software system for mathematical calculations [14]. The toolboxes of the software system ensure ACS calculation and simulation. It is also possible to generate real-time software using the Matlab Simulink Coder system toolbox.

5. Development, calculation and optimization of a TP for APG processing and synthesis of ACS

5. 1. Development of the TP schematic diagram

The products of the LGPP TP include commercial methane, technical propane-butane and an uncertified gas. The LGPP control systems should be able to work at heavy disturbances to the changes in flow and concentration. Analysis shows that it is expedient to produce methane and propane-butane using a single-column installation. The proposed hardware design of the TP for APG separation is shown in Fig. 2.

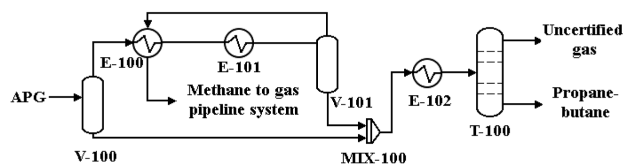


Fig. 2. Manufacturing scheme of processing associated petroleum gases for local gas processing plants: V-100 — incoming separator; E-100 — gas/gas heat exchanger; E-101 — refrigerator; V-101 — low-temperature separator; MIX-100 — gas mixer with a decrease in pressure; E-102 — gas heater; T-100 - distillation column

After its compression to 4 MPa, the purified and dried APG enters the separator. Propane and butanes mainly become liquid at such pressure, which allows them to be roughly separated from methane and ethane. From the top of the separator, the gas is directed to a gas/gas heat exchanger where it is cooled by the gas from a low-temperature separator. Further cooling takes place in the refrigerator. At the top of the low-temperature separator, pure commercial methane is exuded. At the bottom, there is a liquid-phase mixture of gases which is mixed with the liquefied gas entered from the inlet separator. The resulting mixture is heated and fed to the DC. The lower product of DC is propane-butane and the upper product is the uncertified gas for the use at thermal power-stations or boiler houses.

5. 2. Calculation of main TP parameters

The calculation is based on information about the necessary requirements to the product compositions. The calculation results in obtaining parameters of material flows and the processing devices meeting the requirements. Since the TP prepares two products, it is advisable to divide it into two sections: methane emission and propane-butane emission respectively. The product of the first section is a gas with methane content above 0.9 molar fractions (mol. fr.). The product of the second section is propane-butane. A fragment of the scheme with the results of calculating the methane emission section is shown in Fig. 3.

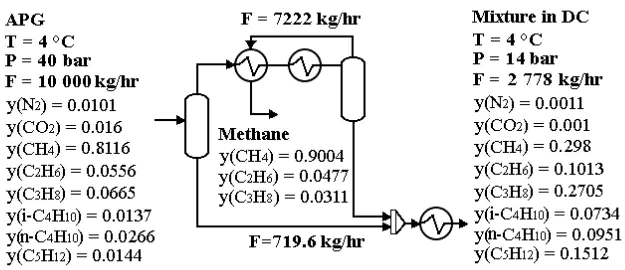


Fig. 3. The main results of calculating the section of commercial methane emission for the gas transportation system with indication of composition of the main components in mole fractions

To simplify perception, the results of calculation of control and reducing valves as well as energy consumptions for heat exchange are not given there.

5. 3. Analysis of disturbances and optimization of condition parameters of the process units

The peculiarities of APG production include variable flow rate and composition of the produced gas. For example, the content of C_{3+} hydrocarbons can vary in the range from 0.1 to 0.6 kg/m³. This variation has both a one-time and a recurrent nature. As a rule, flow deviation is within 10–20 %. Thus, when calculating valves and pipelines, it is necessary to ensure principal operability of installations under the influence of disturbances.

Analyze influence of the main disturbances.

1. A change in concentration with a growth of ethane contribution can result in a loss of methane quality. It can also bring about instability of ACS.

2. The change in consumption does not affect methane quality but it affects efficiency of the DC plates, which can bring about changes in the composition of the output products.

3. Changes in temperature of the heat exchanger agents, condensers, pressure drops in the reboiler steam pipeline lead to a change in the temperature conditions, which affects quality of product separation, the rate of steam supply and can result in DC flooding when the vapor flow prevents the liquid runoff.

The DC is the main apparatus of the second section. When calculating the DC, the following initial data are used: concentration, flow, temperature and pressure of the feed as well as mole fraction of ethane in the distillate. The parameters to be optimized include the number of plates and the reflux ratio. For optimization, a program has been developed that changes the optimization parameters in a specified range in the initial file of the Chemsep software and analyzes obtained calculation results. The optimization results are shown in Fig. 4. The numbers around the color points mean the reflux ratio.

As can be seen, there is a weakly nonlinear dependence between the reflux temperature and propane concentration. Assume that reflux cooling below –30 °C is inexpedient in view of high refrigerant costs. This will lead to a loss of ¼ propane in the distillate but will be economically justified. Then the combination of 15 theoretical plates and the reflux ratio of 1.5 will be optimal. However, since the calculation did not take into account pressure drop in the column, that is, the pressure was assumed to be constant (14 bar), then choose for reserve the reflux ratio of 1.4. The theoretically average efficiency factor of the plates for this configuration is 0.6674. Thus, the number of real plates is 20.

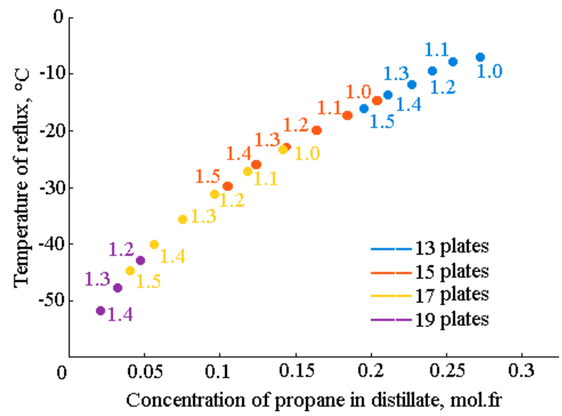
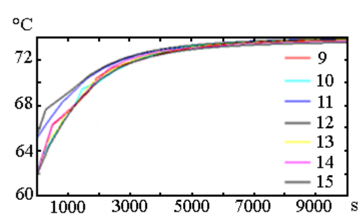


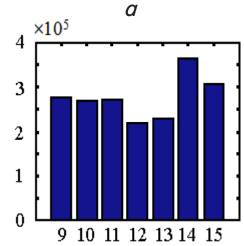
Fig. 4. Results of optimization of the TP distillation column

When the calculated design parameters are transferred to the USTPS, the data of the product flows almost coincide due to DC calculation in USTPS. In accordance with the recommendations of [15], introduce the plate diameter (1.195 m), distance between the plates (0.6 m), the condenser volume (3.2 m^3) and the reboiler volume (7.2 m^3) into the DC parameters of the USTPS.

One of the parameters affecting quality of ACS operation is the feed plate number [16]. Take the minimum deviation of concentration when the control actions change as a criterion of controllability, which will increase self-regulation of the DC without ACS intervention. The result of the experiment with the channel most closely related to propane concentration is shown in Fig. 5.



a



b

Fig. 5. The results obtained in optimizing dynamics of the distillation column: *a* – temperature transient processes of the column bottom when there is an increase in steam consumption by 10 % for different numbers of the real feed plate (numbering is above); *b* – deviation integral depending on the number of the feed plate

Thus, according to the chosen criterion, the real feed plate number 12 will be the optimal one. Since the quality of ACS transients can also be improved by increasing the number of DC plates, then if it is not possible to achieve an acceptable ACS quality at the stage of its synthesis, a higher number of DC plates can be tried [17].

5. 4. Choice of a strategy for TP parameters control

The TP produces two main products: methane and propane-butane. For separation of commercial methane, it is necessary to control temperature conditions of heat exchangers. Level control in separators is not practical since the control system must ensure operation over a wide range of APG flows and concentrations.

There are two strategies of selecting variables for controlling the DC extracting propane-butane: based on direct or indirect quality control of the final product.

The direct strategy is more common since concentration stabilization coincides with the purpose of the distillation column operation. A gas chromatograph is used to measure concentration of products in the TP. The sensor is inertial (the analysis time is 5–15 minutes). Special gas preparation is required for the measurement (achievement of the preset temperature and pressure conditions). The chromatograph error is 5 %. However, the main problem is ignoring features of the temperature profile (the mixture is separated at the boiling point) which makes unworkable the control systems developed according to this strategy under heavy disturbances. Thus, in order to achieve an acceptable separation quality under real disturbances, it is necessary to stabilize both concentration and temperature [18].

The problem with indirect quality control is that the relationship of temperatures in various zones of the DC with the concentration of products is just approximate. In addition, the systems built based on such a strategy are also inefficient at heavy disturbances since a change in the inlet concentration requires a change in the temperature conditions to achieve the desired product concentration. On the other hand, temperature sensors are reliable, have a small error and a low inertia which simplifies their use in the automatic control systems.

Proceeding from the foregoing, the two-level control system is optimal for the DC. The upper level should stabilize operating condition parameters of the DC to achieve the required concentration. The lower level should ensure stabilization of the temperature conditions of heat exchangers and distillation column. The main requirement to the lower level is provision of fast transients and the top level should feature a maximum simplicity. The system for stabilizing the DC temperature must be operable when stabilization of the product concentration is switched off.

5. 5. Investigation of TP dynamics and construction of simplified linear mathematical models

Three apparatus types are used in TP: separator, heat exchanger and DC. As it was mentioned above, stabilization of levels in separators is inexpedient, therefore study of their dynamics is not required. The mixer also does not need to be controlled. Make a more accurate simulation of dynamics of heat exchangers than HYSYS using the results of [13]. Transfer the results of calculation to USTPS.

Advantage of modern USTPS when solving the problem of DC simulation is that the calculation methods in USTPS are repeatedly calibrated according to the production data. Comparison of behavior of real DCs and simulating of their dynamics in HYSYS was made in [19, 20]. This comparison demonstrates high accuracy of coincidence of the results of simulating by HYSYS with the behavior of real DCs. Thus, it is advisable to obtain linear models of dynamics directly from the USTPS with a view to the subsequent ACS calculation on their basis. The quality of the ACS work is checked both on linear models and in USTPS.

To conduct an active experiment in HYSYS, both a standard interface for interprogram communication between DDE and ActiveX [21] and the built-in macro language can be used. The mathematical model can be constructed using the methods of the Matlab Identification Toolbox or Simou [22]. The transient processes obtained from HYSYS with the growth of distillate, condenser refrigerant and reboiler steam consumption (%) are shown in Fig. 6. In addition, Fig. 6 shows the transient processes calculated from the channel models. The models used included those obtained by the Simou method and the approximated models in the form of an inertial link of the first order plus dead time model (FOPDT model). In the case when the transient process was close to one of the differential link, the test Matlab function was used.

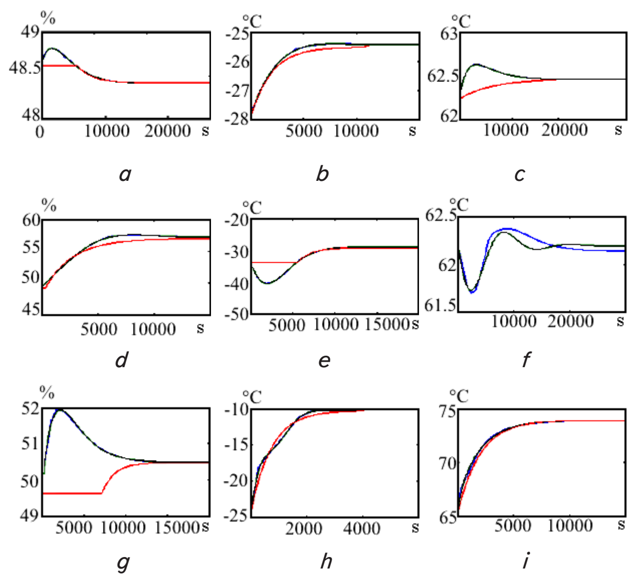


Fig. 6. The results of simulating the distillation column and its approximated models: *a* — level in the condenser with an increase in the distillate consumption by 10 % of the nominal; *b* — reflux temperature with increase in distillate consumption by 10 % of nominal; *c* — bottom temperature with an increase in distillate consumption by 10 % of the nominal; *d* — level in the condenser with an increase in refrigerant charge to the condenser by 10 % of the nominal; *e* — reflux temperature with an increase in refrigerant charge to the condenser by 10 % of the nominal; *f* — bottom temperature with an increase in refrigerant charge to the condenser by 10 % of the nominal; *g* — level in the condenser with an increase in steam flow to the reboiler by 10 % of the nominal; *h* — reflux temperature with an increase in flow rate of steam to the reboiler by 10 % of the nominal; *i* — bottom temperature with an increase in flow rate of steam to the reboiler by 10 % of the nominal; — USTPS; — exact linear model; — FOPDT model

The simulation results show that the DC dynamics can be represented by linear links when the deviation of controls is 10 %. Most of the channels can be described by a link of the first order with a delay (or without it). The deviation of controls in the opposite direction makes it possible to obtain close models, so the object can be considered almost linear in the considered range of deviations of the control actions.

5. 6. Synthesis of ACS controllers

Perform synthesis of ACS by a heat exchanger using an engineering technique that takes into account robustness factor [13].

For the synthesis of DC ACS, select the first-level control channels using the PID family controllers based on the models obtained. Make the choice based on the gain value taking into account the proximity to linearity of the static characteristic. Then the control channels are "steam flow into the reboiler – bottom temperature", "distillate consumption – reflux temperature" and, despite some non-linearity, "refrigerant flow rate – level in the condenser".

Develop two lower-level ACS based on PI (due to the large inertia of the channels) and linear-quadratic regulators.

Make the initial tuning of the PI-controllers by an engineering method [23] without taking into account the interconnection of the channels. Such tuning does not ensure obtaining qualitative transients but the subsequent tuning of the integration time in two controllers gives a satisfactory solution. Further, improvement in quality of operation of the controllers will be obtained by solving the problem of parametric optimization. The ranges of variation of controller parameters are taken in the range −50...+300 % of those calculated by the engineering method. As a result of optimization, quality of stabilization improves significantly.

Calculate the linear-quadratic regulator (LQR) on the basis of the recommendations of [24] where a procedure for the synthesis of a robust ACS for strongly interrelated control objects was proposed. The calculated regulator provides a satisfactory control quality and is robust.

Fig. 7 shows the transient processes obtained by increasing the task by three units for all controlled variables using the following ACS variants:

– decentralized system on the basis of PI-controllers settings of which were obtained by an engineering method;

– decentralized system on the basis of PI-controllers, the settings of which were obtained by solving the optimization problem;

– robust multivariable control system based on a linear-quadratic regulator.

The transient processes analysis (Fig. 7) shows that the best control quality was obtained in the control system with optimized settings of PI controllers. The robust multivariable control system based on the linear quadratic regulator has more inertial processes although there is more reserve for the control action in it.

To ensure operability of the DC ACS at heavy disturbances, it is necessary to stabilize the following parameters at the upper level of the ACS: pressure, propane concentration in the upper product and level in the reboiler. This can be achieved by using cascaded PI controllers, which will represent the upper level of the ACS.

Pressure is directly dependent on the cooling quality of the distillation column, so its stabilization can be realized by a cascade control of level in the condenser.

Propane concentration in the upper product depends on both the top and bottom temperatures. Although connection of concentration with the steam flow rate to the reboiler is strong, it is safer to stabilize concentration according to the reflux temperature. A mismatch between the top and the bottom temperatures leads to an increase in the liquid level in the reboiler which can disrupt the DC operation, therefore, it is necessary to correct the task for the bottom temperature in order to prevent rise of the liquid level. Thus, the scheme of automating the TP of APG processing will take the form shown in Fig. 8.

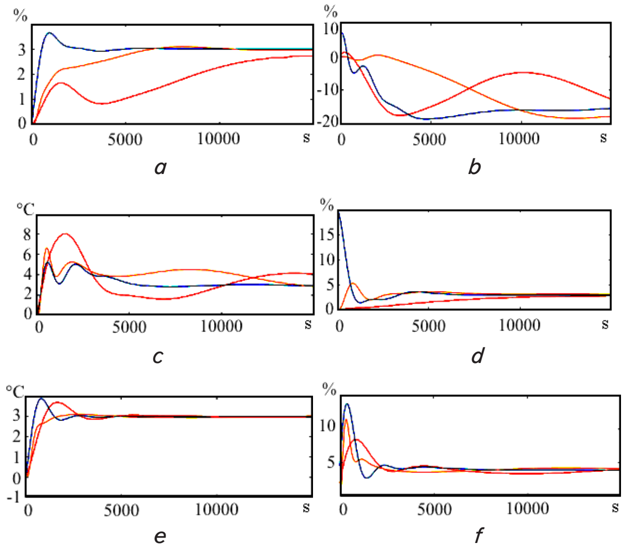


Fig. 7. Transient processes when the task is changed by 3 units for all controlled variables (simulation using an exact linear model): *a* – deviation of temperature level in the condenser; *b* – deviation of distillate consumption; *c* – deviation of the reflux temperature; *d* – deviation of refrigerant consumption in the condenser; *e* – deviation of the bottom temperature; *f* – deviation of steam consumption in the reboiler; ▬ PI-optimal; ▬ PI-engineering; ▬ robust LQR

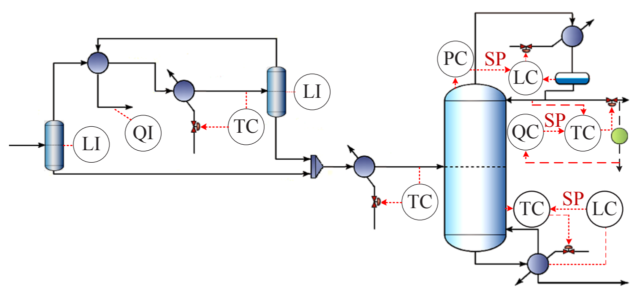


Fig. 8. Scheme of automation of the technological process of processing associated petroleum gases for local gas-processing plants

The settings of the upper level controllers and the temperature controllers for the low-temperature separator feed and DC were obtained by an engineering method and their optimization does not improve quality of the transient processes in the automatic control system.

6. Quality control of transients

Let us verify the quality of transient processes in USTPS in two stages: for the lower level when tasks are changed and for a two-level ACS at maximum perturbations.

6. 1. Quality control of transient processes of the lower level of the automatic control system

To model ACS with PI controllers, use standard blocks of the USTPS PID-controller indicating the corresponding settings in them. To simulate the automatic control system with a robust multivariable LQR, its software implementation was made using the WrapBasic programming language built into the HYSYS USTPS.

Fig. 9 shows the transient processes when using PI-controllers with optimized settings when the task changes according to the column bottom temperature by 0.1, 1 and 3 °C, respectively.

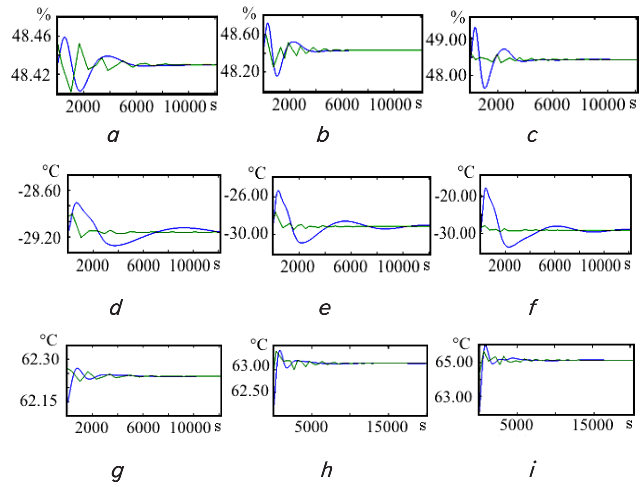


Fig. 9. Transient processes in automatic control systems based on PI-controllers when the task for the temperature of the distillation column bottom changes: *a* — the level in the condenser when the task is changed by 0.1 °C; *b* — level in the condenser when the task is changed by 1 °C; *c* — level in the condenser when the task is changed by 3 °C; *d* — reflux temperature when the task is changed by 0.1 °C; *e* — is the reflux temperature when the task is changed by 1 °C; *f* — reflux temperature when the task is changed by 3 °C; *g* — level in the condenser when the task is changed by 0.1 °C; *h* — level in the condenser when the task is changed by 1 °C; *i* — level in the condenser when the task is changed by 3 °C; ▬ simulating on a linear model; ▬ simulating in USTPS

The simulation results (Fig. 9) show that the transients in two simulation variants coincide the more the larger is the reference value. The greatest coincidence is for the channels the contribution to the control of which is maximal. This discrepancy is due to the nonlinearity of the DC dynamic characteristics. Nevertheless, the control quality at simulation in USTPS was improved in comparison with the system simulated on the linear model in Matlab.

Fig. 10 shows transient processes when using LQR with the same changes in the reference for the DC bottom temperature.

The results of simulating the ACS in Matlab and in HYSYS USTPS shown in Fig. 10, *a–i* coincide better. On the other hand, the transient process, when the task is deviated by 3 °C, becomes self-oscillating in the reflux temperature. This is considered bad for the systems based on the strategy of temperature stabilization.

Thus, as a result, the control system based on PI-controllers proves to be more rapid, especially for small deviations of references, therefore it is expedient to use it for the lower level.

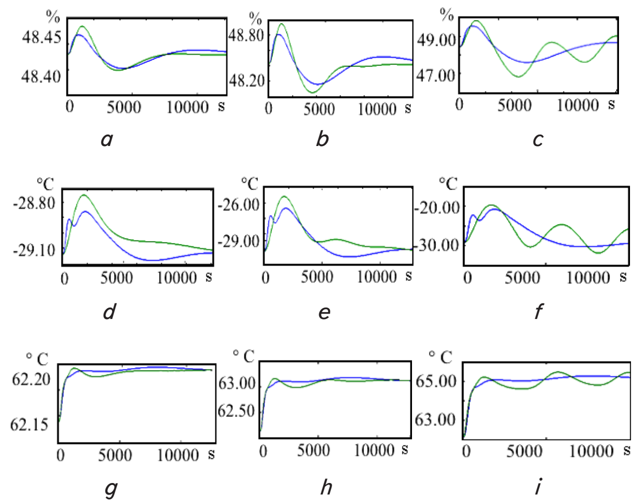


Fig. 10. Transients in automatic control systems on the basis of a robust linear-quadratic regulator when changing the reference for the distillation column bottom temperature: *a* — level in the condenser when the task is changed by 0.1 °C, *b* — level in the condenser when the task is changed by 1 °C, *c* — level in the condenser when the task is changed by 3 °C, *d* — reflux temperature when the task is changed by 0.1 °C, *e* — reflux temperature when the task is changed by 1 °C, *f* — reflux temperature when the task is changed by 3 °C, *g* — level in the condenser when the task is changed by 0.1 °C, *h* — level in the condenser when the task is changed by 1 °C, *i* — level in the condenser when the task is changed 3 °C; ▬ simulating with a linear model; ▬ simulating in USTPS

6. 2. Checking quality of transient processes for the two-level ACS

Analyze influence of the main disturbances on the DC operation when using a two-level structure in the HYSYS USTPS. To do this, perform simulation for the following disturbances:

– 30 % increase in the mole fraction of methane in the feed;
– 50 % increase in the mole fraction of propane in the feed;
– 50 % increase in the mole fraction of n-butane in the feed;
– 10 °C increase in the feed temperature;
– 30 % decrease in the feed consumption;
– 30 % increase in the feed consumption.

The generalized results of simulation are given in Table 2.

Table 2

Change of operation condition parameters of the distillation column in the control process

No.	Set values of DC ACS parameters at the bottom level when the references are changed			Propane content in distillate (mole fractions)	
	Level in the condenser, %	Reflux temperature, °C	Bottom temperature, °C	Maximum deviation	Stabilization time, s
1	10	–31	62.5	0.011	1900
2	74.3	–29	54.5	0.07	3500
3	39	–29.1	66	0.04	600
4	68	–29.2	62.1	0.003	200
5	10	–30	60.7	0.019	1000
6	74	–29.7	64.1	0.006	2000

The results given in Table 2 show that the automated technological process has ensured production of propane with the required concentration in the distillate in all considered cases.

7. Discussion of the results obtained in development of computer-integrated systems for automation of the technological process of associated gas processing

1. The developed procedure enables creation of an automated technological process of APG processing capable to produce methane and propane-butane of the required quality at large perturbations in flow and concentration of the flows incoming from the oil wells. A number of recommendations in the procedure coincide with the recommendations of [25] describing modernization of distillation complexes. The procedure is focused on the use of medium and small size deposits, typical for Ukrainian conditions.

2. Qualitative APG processing requires a technological calculation, which takes into account not only the criteria of production efficiency, but also the specifics of the ACS synthesis. This conclusion coincides with the conclusion made in [25] where it was noted that it is necessary to consider technology, equipment and automatic control systems in inextricable connection but the ACS synthesis was not considered.

3. For the TP of APG processing for LGPP, a two-level structure of ACS is recommended. The lower level is for stabilizing parameters of units at small disturbances and the upper one is for ensuring operability of the units under heavy disturbances, which is achieved by changing their operating conditions. Advantages of the multilevel architecture coincide with the conclusions drawn in [26]. The paper proposes a cascade concentration control by changing the reference for the temperature controllers with the use of "decoupling". In the considered TP of APG processing, "decoupling" will not be effective because of greater DC nonlinearity, which is characteristic for the hydrocarbon separating DCs. Calculation of the controller parameters by the optimization method taking into account robustness is more efficient and reliable for the considered case.

4. When developing multivariable controllers, it is necessary to take into account nonlinearity of the controlled object channels. Improvement of control quality by taking into account multicoupling of the controlled object is more often possible in the case of stabilization of the DC material balance than the energy balance. The problem of development of multivariable and multicoupled controllers capable of a guaranteed control quality improvement for nonlinear objects requires further studies. A supervisory approach to the ACS synthesis described in [27] is also promising. Its applicability to various DC cases is the direction for further studies.

5. Checking the control system with the use of accurate, calibrated for the data of real TP models implemented in USTPS enables identification of the problems that are not apparent when using linear models. It minimizes the risk of a costly procedure for setting up a production control system which is caused by inadequate accuracy of the control object simulation or the introduced errors. It becomes especially topical for controllers with the quality of control obtained by optimization methods. For example, a method of designing a fuzzy controller of pressure in the DC for separation of hydrocarbon mixtures was proposed in [28]. High-quality transients when using fuzzy controllers can be obtained by using the PSO optimization of the membership function. Effectiveness of such optimization is only possible with the use of an exact nonlinear DC model implemented in USTPS. The use of USTPS additionally enables debugging of the ACS operation after program-technical implementation which is not considered in this study.

6. Computer-integrated TP automation is a promising area of research. Application and improvement of the developed approach will allow acceleration of development of new technological processes and improve quality of their products. The results of the study are recommended for use in organizations that are engaged in the development of TP for APG processing and their automation. Also, the results will be useful to organizations and researchers occupied with distillation columns. It is also possible to use the proposed approach in the educational process of universities.

8. Conclusions

1. A procedure for constructing computer-integrated systems for automating technological processes of processing associated petroleum gas has been developed. The procedure involves computer integration of the process equipment and automatic control systems for the process of APG processing.

The advantage of the procedure is that it enables adaptation, with minimal efforts, the parameters of the LGPP operation conditions to the specifics of a particular field and to the requirements of the finished product market. When performing the procedure, it is necessary to use special software: HYSYS USTPS, Chemsep software for calculating distillation columns, a program for calculation of heat exchangers and Matlab mathematical software.

2. A computer-integrated automated TP of APG processing was developed using the proposed procedure. The process makes it possible to produce commercial methane and technical propane-butane in conditions of instability of flow and concentration of the streams coming from the wells. The results of modeling the developed automatic control system in USTPS show that the developed TP copes with the task. The TP quality is estimated by the value of deviation of the product concentrations in transient processes under the action of maximum disturbances in composition, temperature and APG flow. At a sudden change of the feed temperature in the distillation column of the TP by 10 °C, maximum deviation of concentration of the key component (propane in the distillate) was ~3 % of the nominal value. With an abrupt increase in the molar feed consumption by 30 %, maximum deviation in concentration of the key component was ~18 % of the nominal value, while decrease by the same amount resulted in a ~6 % deviation from the nominal value. The developed ACS also proved to be workable at a sudden change in feed composition (the deviation of components was 30–50 % from their nominal molar fraction). The maximum time of transient processes was 1 hour when there were changes in the composition of feed and the maximum deviation of the concentration of the key component in the cases studied was 10–65 % of the nominal value.

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